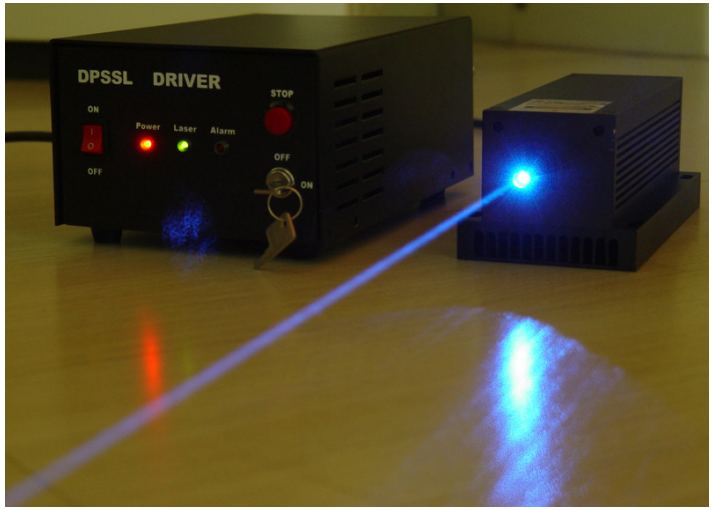
Optical Transmitters and Receivers

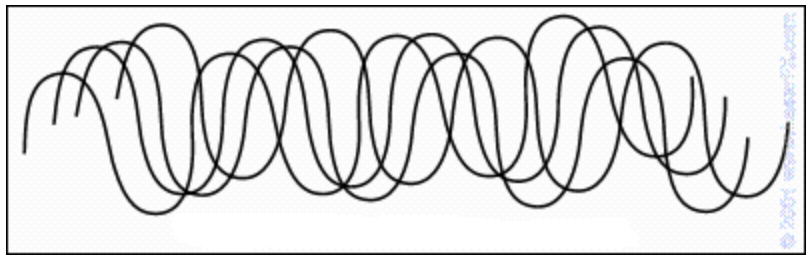
The LASER

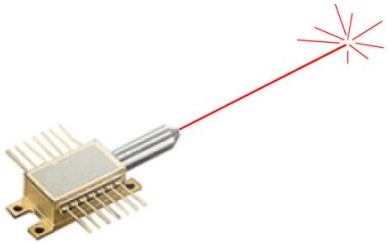
- Light Amplification by Stimulated Emission of Radiation
- Generates coherent light: all photons emitted at same frequency and phase



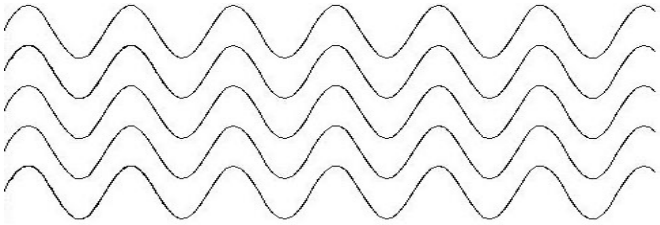
Incoherent vs. coherent light

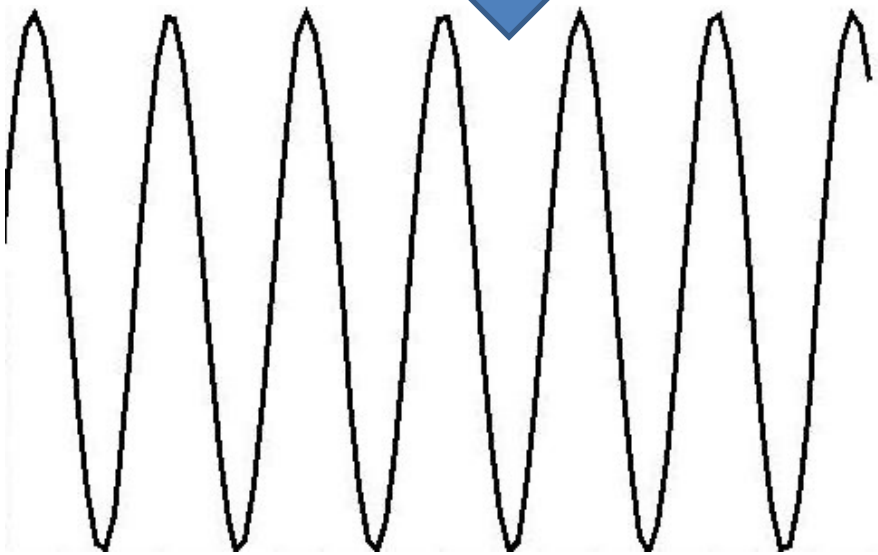
Incoherent light





Coherent light

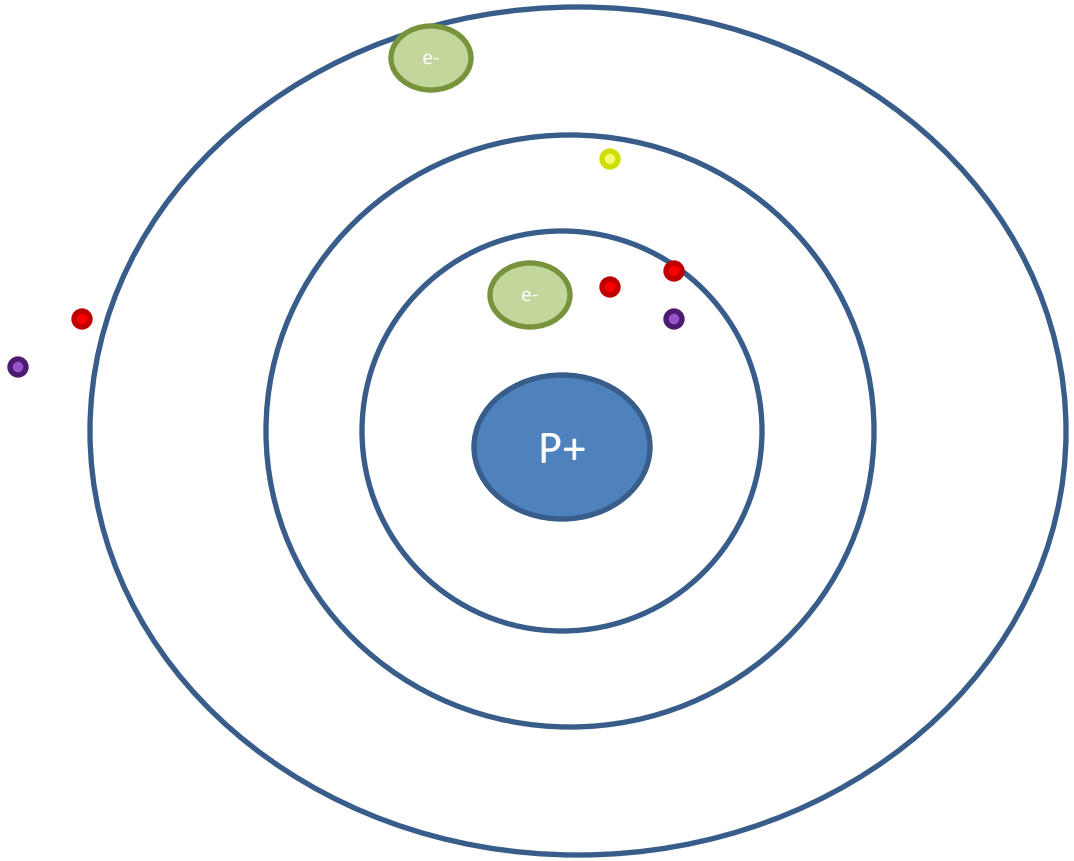




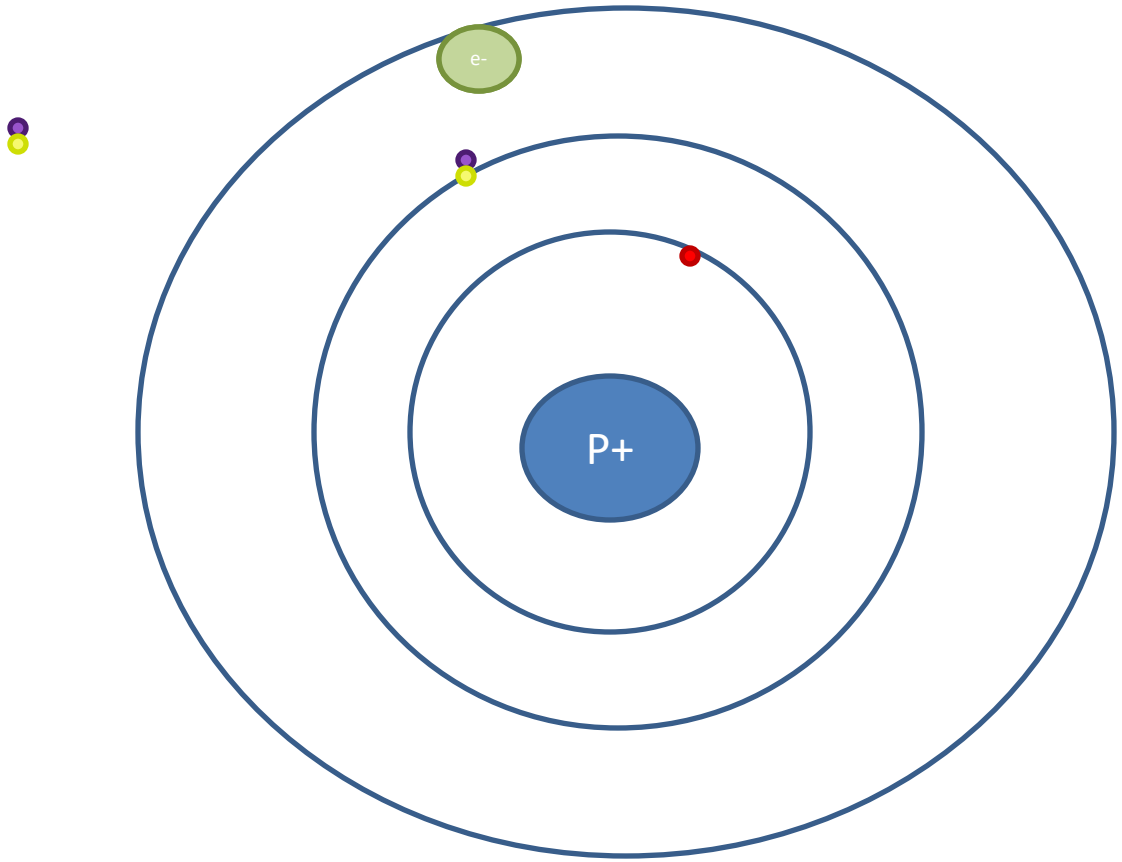
LASER Power

1KW halogen light vs. 1KW laser source

Absorption and emission of radiation



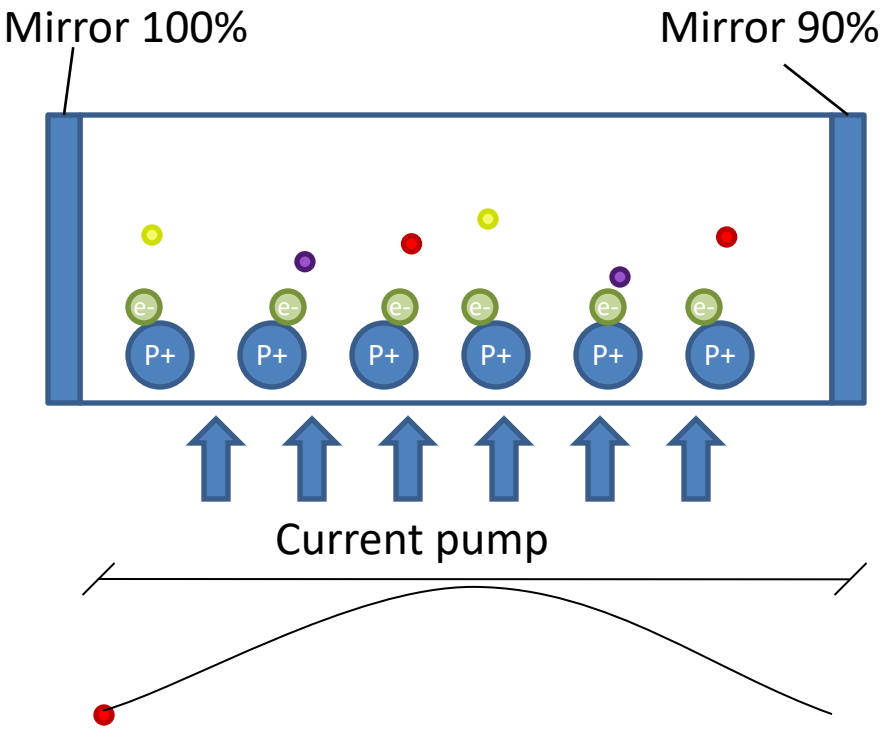
Stimulated Emission of radiation



LASER

Based on survival of the fittest

i.e. the one that fits most ...



The light whose half wavelength matches the length of the laser is the one that is most reflected:

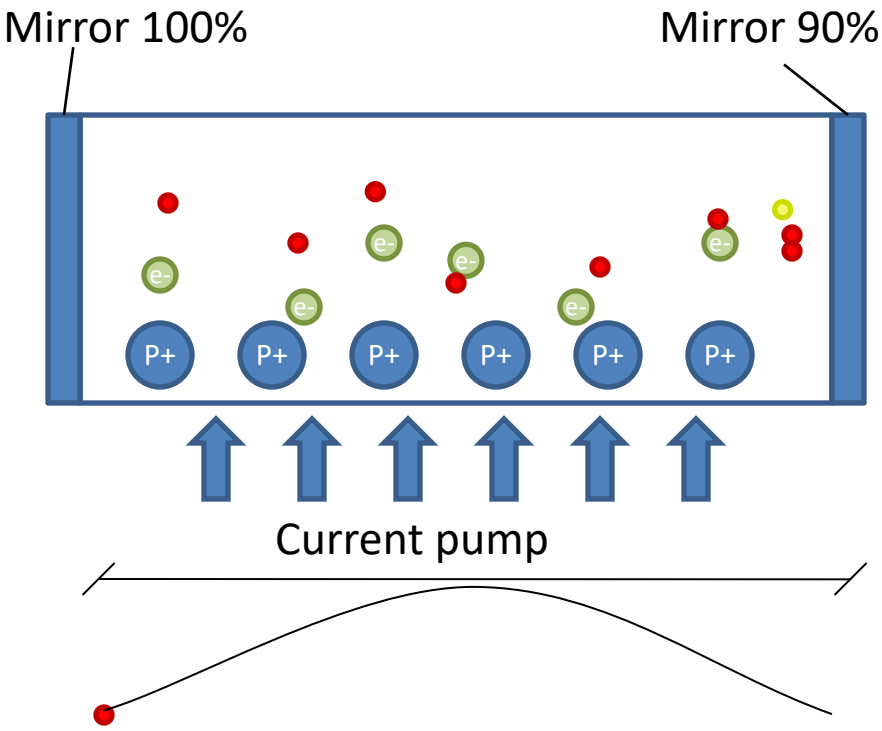
➔ **Resonance**

Suppose wavelength of red photon matches length of laser

Fabry-Perot LASER model

Based on survival of the fittest

i.e. the one that fits most ...



The light whose wavelength matches the length of the laser is the one that is most reflected:

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LASER

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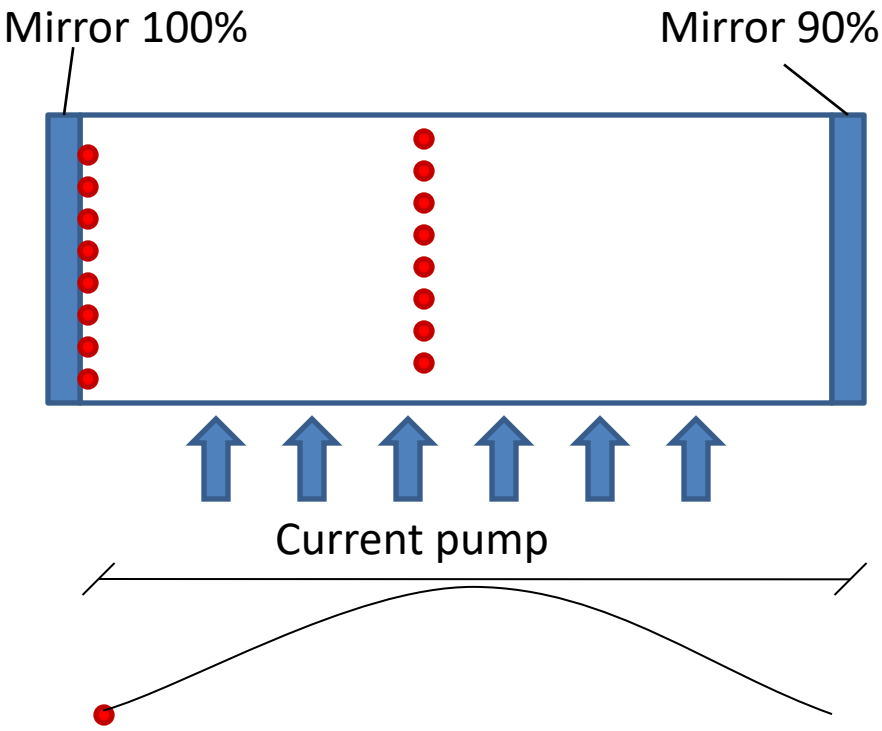


The light whose wavelength matches the length of the laser is the one that is most reflected:

➔ **Resonance**

This is the light produced by the laser

Suppose wavelength of red photon matches length of laser

Tunable lasers

- A tunable lasers can emit light at different wavelengths within a predetermined range

- Are useful for many reasons:
  - Flexibility:
    - One size fits all (favorable both for the manufacturer and the user)
    - Reduces the number of spare lasers needed in WDM systems
  - Reconfigurability: can choose the wavelength most suitable to the network

- The idea is to change the size of the resonant cavity:
  - Mechanically: physically increase the size of the cavity
  - Electronically: electrical current in the laser changes the value of the refractive index, and thus the the electrical size

A laser is: (Mark all that apply)

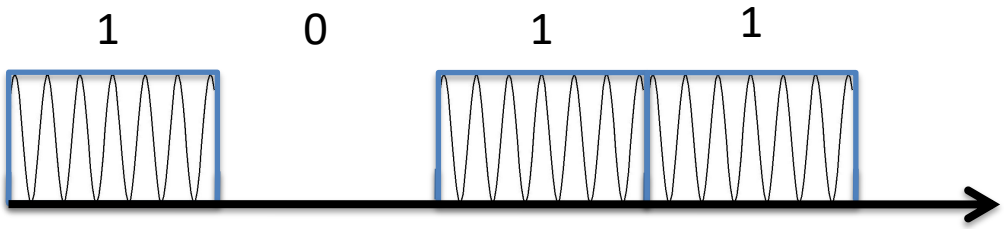
A. A device that emits coherent light
B. A resonant cavity where a current can be pumped to induce population inversion
C. A device used for cutting steel in heavy industry
D. A telecommunication device used to transmit information

Signal modulation

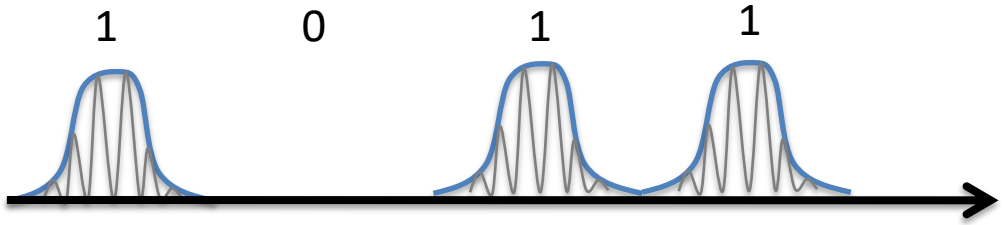
- Modulation is used to add information to a carrier signal.
- Examples of (visible) optical modulation…
  - Produce a change in the light we can see and interpret it as a signal

Laser modulation

- Up until a few years ago on-off modulation was the only modulation used in commercial systems.. and it is still the most common
- Ideally I should transmit square pulses:

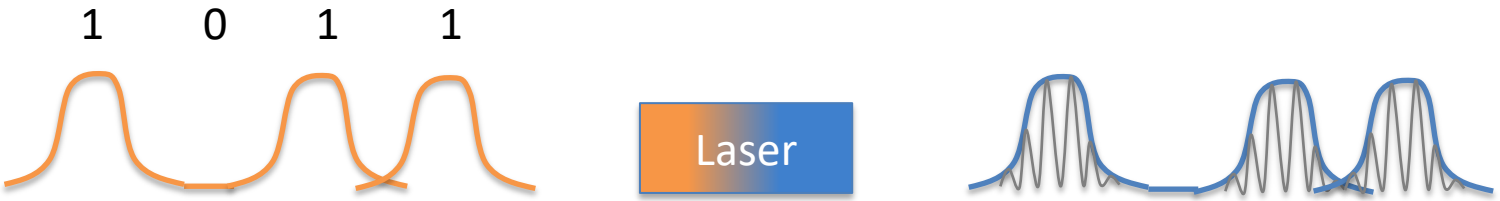


- In practice, because of limitation in response time of the devices they are more Gaussian shaped



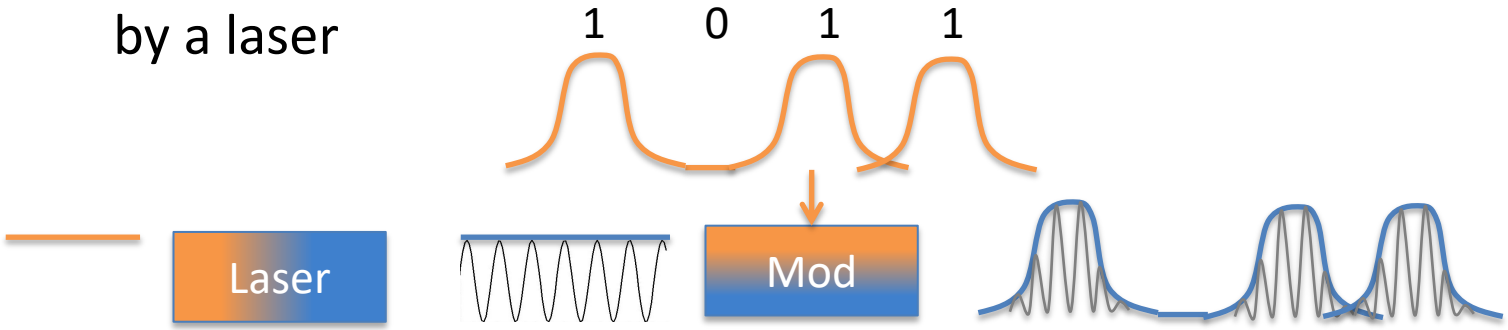
Types of modulators

- Direct laser modulation: switching the power current on and off



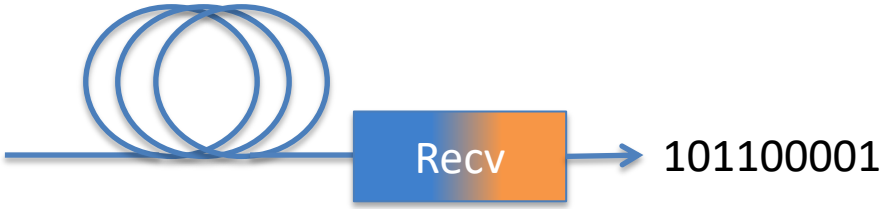
  - Inexpensive (no additional devices required)
  - Since the refractive index depend on the current the pulses generate are "chirped" – the frequency of the carrier varies within the pulse
  - Chirp exacerbates the chromatic dispersion impairment

- External modulation: obscuring intermittently the light generated by a laser

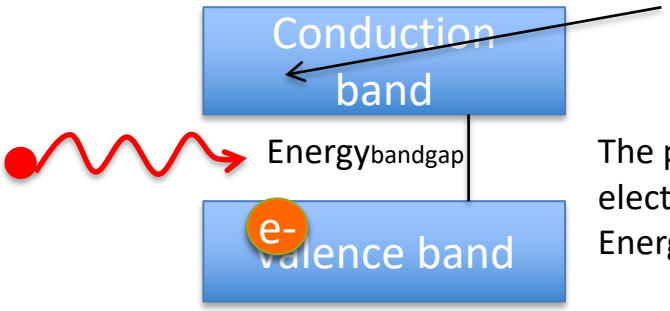


Receivers

- At the end of the link the optical signal is converted to electrical to be processed by network elements (switches, routers) or by end-used equipment



- The element used as a receiver is a photodetector



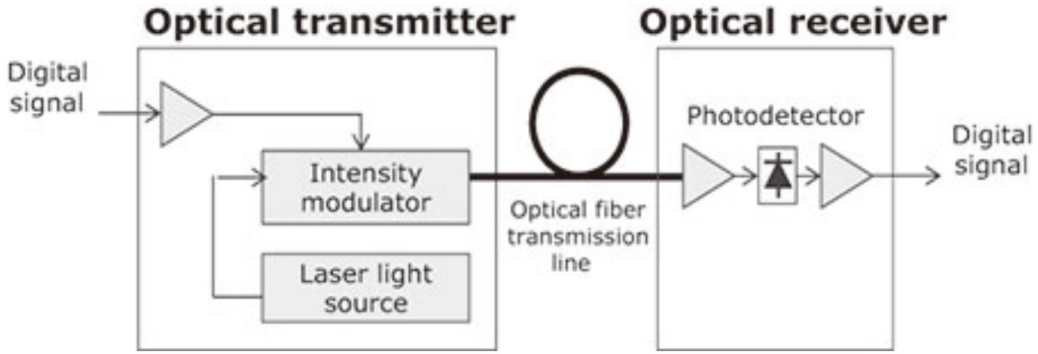
The electron generates an electrical current proportional to the incoming light

The photon needs to carry enough energy to allow the electron to jump from valence to conduction band

$Energy_{photon} > Energy_{bandgap}$

Optical transmission based on Direct Detection (DD)

Only process the amplitude information of the signal



https://www.nec.com/en/global/techrep/journal/recommend_year/2015/07.html

Receiver sensitivity

- Different materials have different bandgap: receivers can be wavelength dependent
- Part of the incoming power P_{in} is absorbed and generates a current I_p
- Responsivity R defined as $R = \frac{I_p}{P_{in}} A/W$, practical values are 1 ÷ 1.2

- The type of receiver we have described so far are called **pin** receiver
- **Avalanche photodiodes (APD)** use large electric field to accelerate electrons/holes and generate a chain reaction, so that each photon can generate more than one electron/hole.
- The drawback is that the variance of the generated current also increases, creating additional noise.

Receiver sensitivity

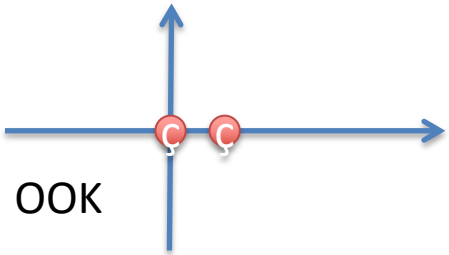
- The receiver sensitivity indicates the minimum input optical power at the receiver necessary to achieve a certain Bit Error Rate
- It also depends on the signal bit rates and it decreases with increasing rate

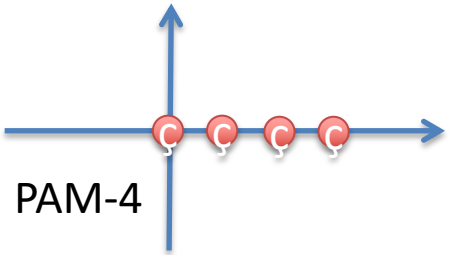
Bit Rate	Type	Sensitivity	Overload Parameter
2.5 Gbps	pinFET	-23 dBm	-3 dBm
2.5 Gbps	APD	-34 dBm	-8 dBm
10 Gbps	pinFET	-18 dBm	-1 dBm
10 Gbps	APD	-24 dBm	-6 dBm
40 Gbps	pinFET	-7 dBm	3 dBm

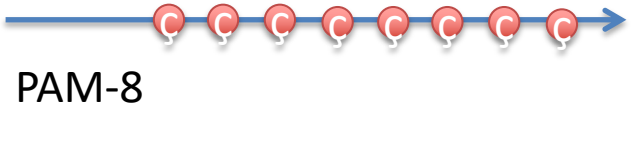
- If the minimum power constraints are met though it doesn't mean that the BER will be achieved, as there are other elements like Signal-to-Noise ratio that influence BER

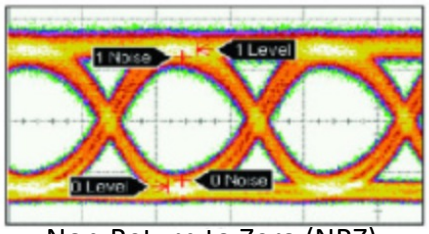
Amplitude modulation

- Low cost system typically only use amplitude for modulating the signal (as we have just shown). The receiver also only consider the pulse amplitude, and are thus called Direct Detection (DD) receivers.
- In these systems I can only use one dimension (i.e., the amplitude) for modulation (on-off keying or Pulse Amplitude Modulation – PAM)

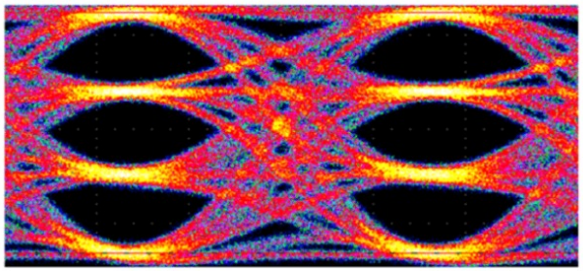


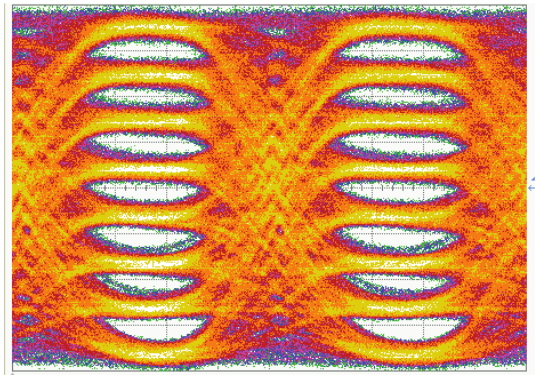


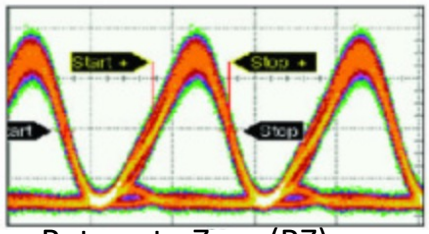




Non-Return to Zero (NRZ)





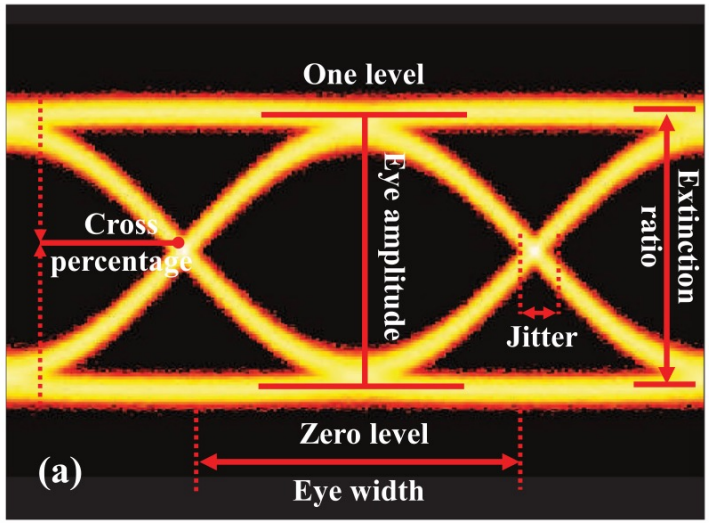


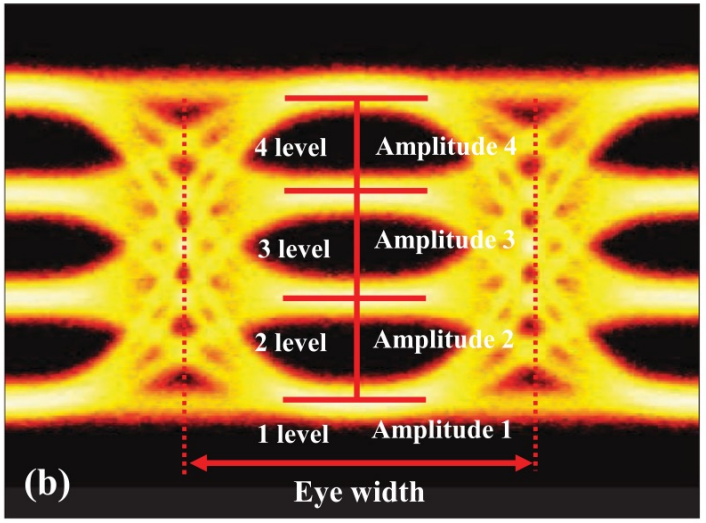
Return to Zero (RZ)

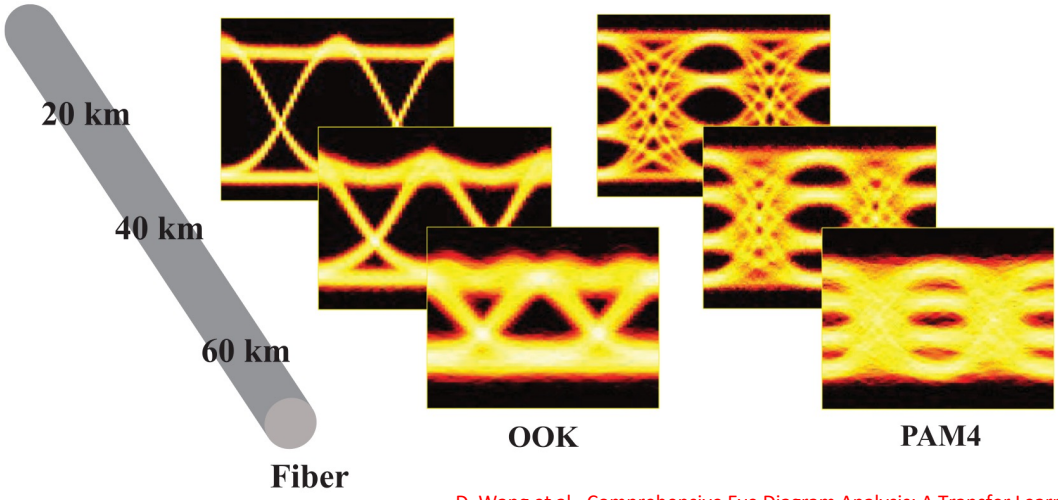
Yu Yu, et al. "Simultaneous multiple DWDM channel NRZ-to-RZ regenerative format conversion at 10 and 20 Gb/s," Opt. Express 17, 3964-3969 (2009)

Eye Diagram

- Plotted by synchronously overlapping multiple transmissions
- It shows how the received signals varies across multiple transmitted symbols





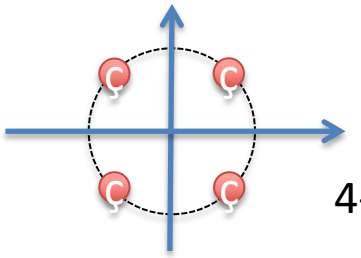


How impairments affect Eye diagram

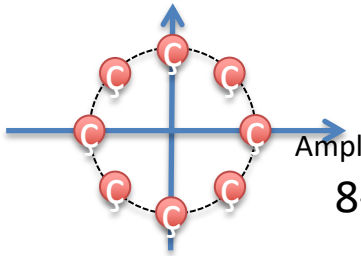
D. Wang et al., Comprehensive Eye Diagram Analysis: A Transfer Learning Approach, IEEE Phot. J. Dec 2019.

Coherent systems

- Over the past few years coherent detection systems have become available: in addition to amplitude, it can detect phase and polarization
- This ability allows to use more modulation formats, such as Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM)



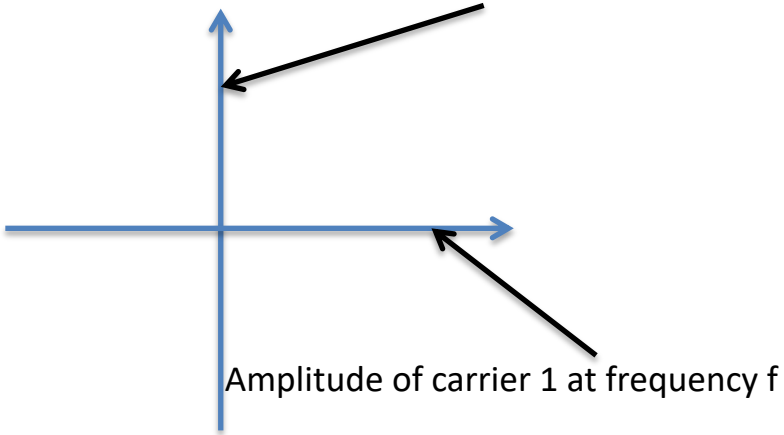
4-PSK



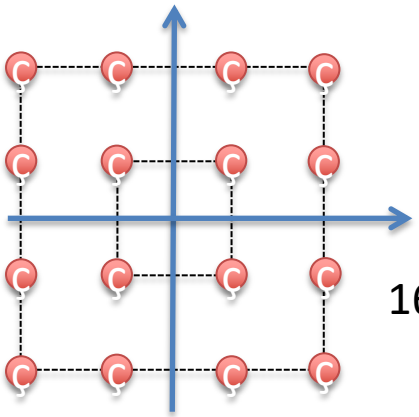
Amplitude of carrier 1 at frequency f

8-PSK

Amplitude of carrier 2 at same frequency
but with 90 degrees offset in phase



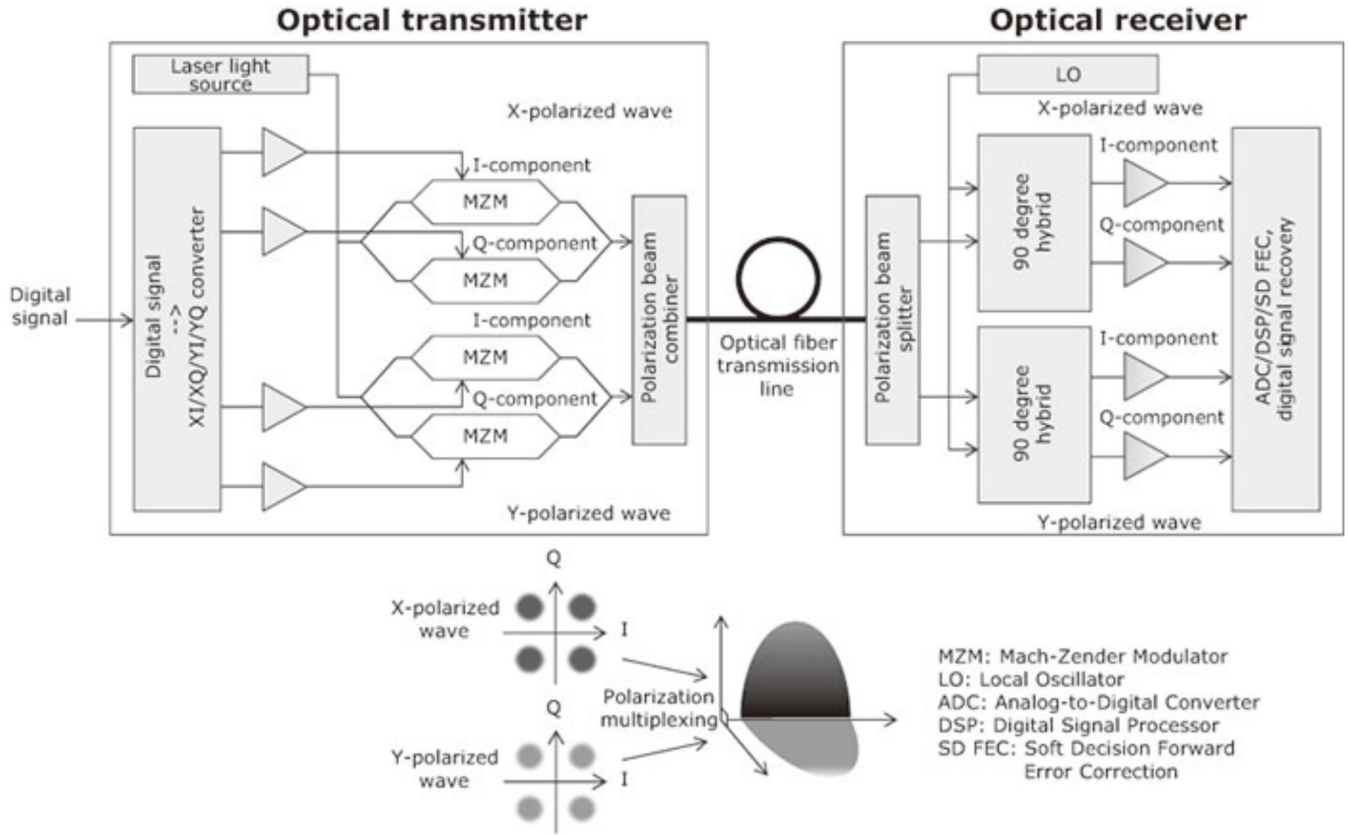
Amplitude of carrier 1 at frequency f



16-QAM

Coherent systems

- Coherent systems are common in the core and metro network (more expensive than DD) with channels of 100Gb/s and above
- However, as cost decreases over time, they will be introduced also in access networks



https://www.nec.com/en/global/techrep/journal/recommend_year/2015/07.html

Advantages of Coherent systems:

- Higher sensitivity compared to DD (the local oscillator provides gain to the received signal)
- Since the phase of the signal is also known, digital signal processing can be applied to counteract the dispersion of the channel
  - Deployment of dispersion compensating fibre can be replaced by DSP operations
  - Great advantages for dynamic networking, where the length of a path and signal baud rate can change dynamically and across signals sharing the same path.
  - Better compensation for nonlinear effects

- The LO is tuned to the receiver frequency, amplifying it ➔ it operates as a filter
- The use of higher order modulation enables higher data rate for the same baud rate
- Spectral shaping: pre-processing to match the channel response in frequency

An optical source needs to be modulated: (Mark all that apply)

A. In order to transmit information
B. In order to reduce the transmission laser linewidth
C. To increase its propagation speed
D. In order to be detected

Where do you think was coherent transmission technology used first

A. In access network transmission
B. In metro network transmission
C. In core network transmission
D. It hasn't been used yet